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Basic cardiac pacing, pacemaker functions and settings

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13–16 minutes

Stimulation threshold

As previously discussed, myocardium may be excited by external electrical stimuli that drive the cells to threshold. **Stimulation threshold** is the minimum amount of energy required to reach threshold and evoke an action potential. The intensity of the electrical stimulus is described by its **amplitude** (measured in volts) and **duration** (measured in milliseconds). The amplitude and duration of the pulse must be optimized to ensure depolarization while minimizing battery consumption. Amplitudes are normally below 1.5 V and pulse duration (width) is usually set to 0.5 ms.

The relationship between current (I), voltage (V) and resistance (R) is described by Ohm's law:

$V = I \cdot R$

Pacemakers generate a constant voltage (V). The current that is delivered by the pulse generator can be calculated as follows:

$I = V/R$

Given that voltage (V) is constant and battery depletion must be minimized, most pacemakers use lead tips with high resistance (400 to 1200 Ω). The higher the resistance in the lead tip, the smaller the current used.

Software settings

The pacemaker software includes pre-programmed algorithms and settings, which can be tailored to the patient's needs. Programming is done through an external device that communicates wirelessly with the pacemaker. A wide range of settings can be adjusted. These settings include the *base rate* of the pacemaker (the lowest heart rate allowed, which triggers the pacemaker), the behavior of the pacemaker at low and high heart rate, the behavior of the pacemaker in the presence and absence of intrinsic cardiac activity, Modern pacemakers are packed with algorithms that optimize the function. For example, there are functions that continuously reassess stimulation threshold in order to calibrate stimulations according to the excitability of the myocardium.

The functions of a pacemaker depend on the software, hardware, and programming. The simplest pacemaker systems consist of a pulse generator and one lead, which is located either in the right atrium or the right ventricle. Such systems are referred to as **single-chamber systems**. Nowadays, most implanted pacemakers are **dual-chamber systems**, meaning that two leads are used: one in the atrium and one in the ventricle. Dual-chamber systems offer the possibility of sensing and pacing in both the atria and ventricles.

Sensing

The pacemaker can record intrinsic cardiac activity and response appropriately. Specifically, the pacemakers sense intrinsic depolarizations. Depolarizations are represented by the P-wave (atrial lead) and QRS complex (ventricular lead). T-waves reflect repolarization and should not be sensed by the pacemaker.

Sensing is used to inhibiting or triggering pacing pulses. The inhibition of pacing is appropriate when there is intrinsic cardiac activity; the presence of spontaneous atrial or ventricular activity should inhibit pacing in the chamber with activity. However, sensing of spontaneous atrial activity (P-waves) without subsequent ventricular activity (QRS) should result in pacing in the ventricles.

To sense correctly, the pacemaker must detect near-field depolarization currents (P or QRS), and ignore near-field repolarization currents (T-waves), as well as far-field currents (i.e currents generated by tissues that the electrode is not connected to). Also, external signals from electronics (cell phones, computers, etc) must also be ignored. The atrial lead is therefore set to record signals with an amplitude range of 1.5 to 5 mV, and frequency 80 to 100 Hz. The ventricular lead records signals in the 10- to 30-Hz range and 5 to 25 mV amplitude. The pacemaker will not sense depolarization outside these boundaries, which may lead to **undersensing** of true intrinsic activity and thus inappropriate pacemaker activity.

As discussed in the previous chapter, the delivery of pacing pulses can be bipolar or unipolar. Sensing can also be bi- or unipolar. Generally, sensing is more accurate with bipolar pacing, due to the fact that both points of measurement are within the heart (i.e both electrodes are located at the lead tip).

Base rate

The base rate is the lowest heart rate allowed by the pacemaker; intrinsic cardiac activity below the base rate will trigger pacing. The base rate is usually set to 60 beats/min, meaning that the pacemaker will wait just 1000 ms after each depolarization before it delivers a pulse. Spontaneous depolarizations occurring within 1000 ms will inhibit the pacemaker.

Triggering

The pacemaker can also be triggered, which means that it paces in the ventricle in response to intrinsic atrial activity. Upon sensing intrinsic atrial activity, the pacemaker stimulates the ventricle after a time delay in order to mimic the physiological delay in the AV node. Triggering allows for the ventricles to follow atrial activity, which is desirable.

Triggering may become inappropriate in the following situations:

- During supraventricular tachyarrhythmia (eg, atrial fibrillation): the pacemaker can transfer the arrhythmia to the ventricles, which is highly inappropriate.
- If the depolarization from ventricular pacing propagates back to the atria, then atrial sensing may trigger a new ventricular stimulation. This cycle can repeat itself and cause an endless tachyarrhythmia.

To prevent inappropriate triggering, the pacemaker has three protective mechanisms:

1. **PVARP**: Atrial sensing is off (refractory) from the beginning of the QRS complex until a period after the QRS is completed. This refractory period, illustrated in Figure 1, is called **PVARP (Post-Ventricular Atrial Refractory Period)**. If the ventricular impulse travels back into the atria during PVARP, the atrial electrode will ignore the impulse. The atrial electrode actually ignores all impulses in the atria (e. g. impulses from an atrial fibrillation) during PVARP. Last but not least, this also prevents the atrial electrode from sensing, and reacting to, ventricular depolarizations.
2. **Max rate**: The pacemaker can be set to a maximum trigger limit. Regardless of atrial activity, the pacemaker will not pace at a frequency above that rate.
3. **Mode switch**: Some pacemakers have a mode switch function that allows triggering to be switched off during a supraventricular tachyarrhythmia.

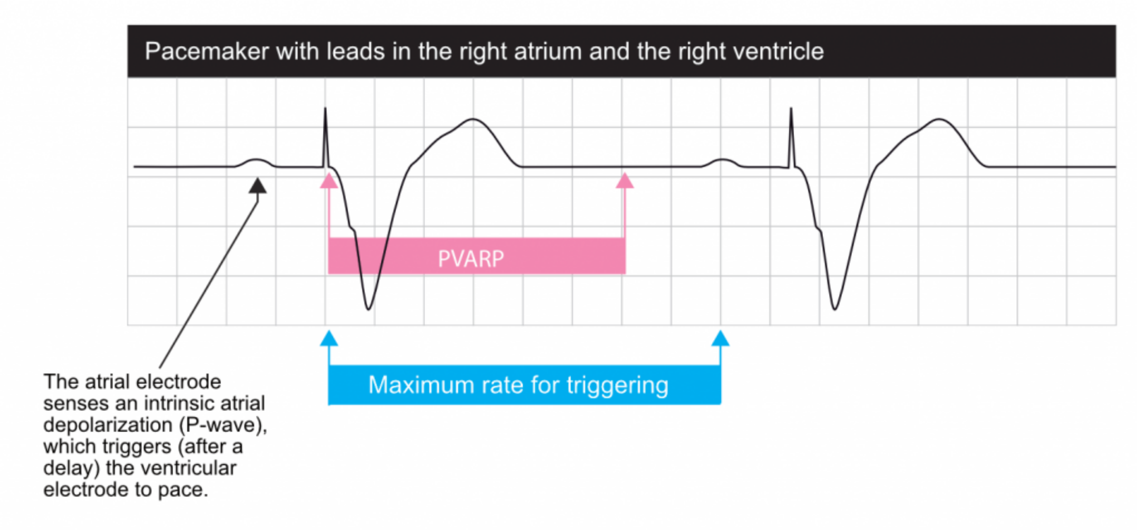


Figure 1. During PVARP, the atrial electrode is refractory, meaning that sensing is off. The period illustrating the maximum rate for triggering is also depicted.

Pacing mode

Pacing mode is declared by an abbreviation consisting of 3 to 5 letters. These letters describe, in chronological order, the following:

1. **The chamber paced**: O (omitted), A (atrium), V (ventricle) or D (dual, atria and ventricles)
2. **The chamber sensed**: O (omitted), A (atrium), V (ventricle) or D (dual, atria and ventricles)
3. **Response to sensed events**: O (omitted), I (inhibited), T (triggered) or D (dual, inhibited and triggered).

4. **Rate responsiveness**: O (omitted, none) or R (rate responsive)
5. **Multisite pacing (pacing in multiple places in the same chamber**: O (omitted), A (atrium), V (ventricle) or D (dual, atria and ventricles)
6.

If the pacemaker is not rate responsive, then the fourth letter may be omitted. This also applies to the fifth letter (multisite pacing).

Example: A DDDR pacemaker:

D = Dual pacing (pacing in the atria and ventricles).
D = Dual sensing (sensing in the atria and ventricles).
D = Dual response (can be both inhibited and triggered).
R = Rate responsive (the pacing rate can adapt to physical activity).

In clinical practice, **DDD**, **VVI**, and **AAI** are most common, with or without rate responsiveness.

Asynchronous pacing

A pacemaker with **AOO** setting stimulates in the atrium but has no sensing and thus no response to sensing. Such a pacemaker stimulates with a fixed frequency, regardless of intrinsic cardiac activity. This is called **asynchronous pacing** because it is not synchronized with intrinsic cardiac activity. Similarly, **VOO** provides asynchronous pacing in the ventricle, and **DOO** provides asynchronous pacing in the atria and ventricles.

Asynchronous pacing is rarely used but it can be useful when there is insufficient intrinsic cardiac activity but extensive disturbances (which would otherwise inhibit pacing). Then asynchronous pacing is suitable because it stimulates at a fixed rate and ignores the signals of the surrounding. Asynchronous pacing also sets in when the battery is drained, or when a pacemaker magnet is placed on the can (note that the effect of a pacemaker magnet may vary according to the manufacturer).

Common single-chamber systems

Pacemaker with **AAI** has one electrode in the right atrium. The electrode is used for pacing and sensing, and the pacemaker is inhibited when spontaneous atrial activity (P-wave) is sensed. If atrial activity is slower than the basic rate of the pacemaker, then the pacemaker will pace.

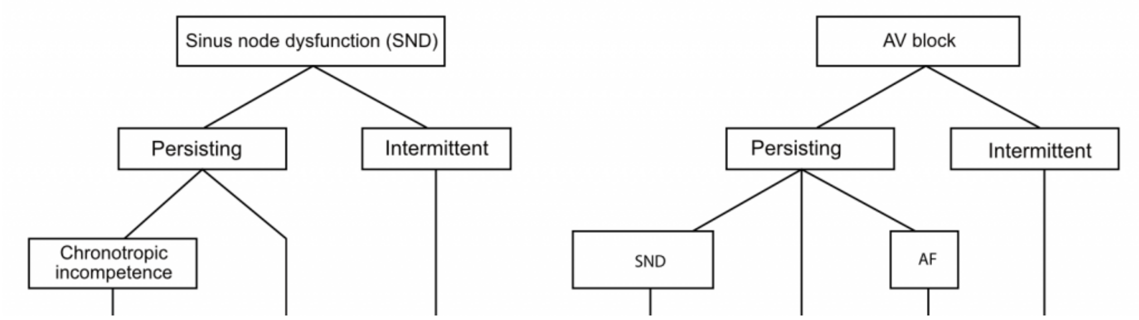
A VVI pacemaker stimulates and senses in the chamber and if it senses spontaneous ventricular activity (R-wave), it does not stimulate. If the ventricular rate is slower than the base rate, then the pacemaker will pace.

Dual-chamber system

The most common two-chamber system is **DDD**, which implies pacing in the atria and ventricles, sensing in the atria and ventricles, and the ability be inhibited or triggered. This pacemaker stimulates in the atria and ventricles if the intrinsic heart rate is below the basic rate of the pacemaker. If the spontaneous heart rate is faster than the basic rate of the pacemaker, then the pacemaker is inhibited. If spontaneous atrial rate is below the base rate of the pacemaker, then the pacemaker will pace in the atrium. It then awaits activity in the ventricle and, if it does not sense ventricular depolarization within a period of time (see *AV delay* below), it will also stimulate in the chamber. If the atrial rate exceeds the baser rate of the pacemaker but ventricular rate does not, then atrial pacing is inhibited, but ventricular pacing is triggered.

DDI pacemaker offers pacing and sensing in the atria and ventricles and can also be inhibited if spontaneous activity occurs. Atrial activity will not trigger ventricular pacing. However, the pacemaker will pace in the ventricle if it does not sense a ventricular impulse within a certain period of time after atrial pacing.

The choice of a pacemaker depends on the underlying disease. The following flow chart is recommended by the European Association for Cardiology, and it is in line with guidelines issued by the American Heart Association and American College for Cardiology.



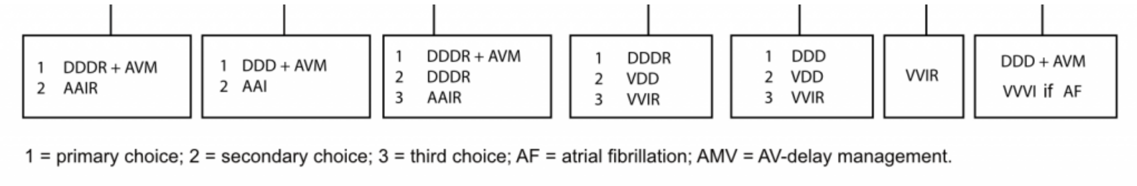


Figure 2. ESC Guidelines – Cardiac Pacing and Cardiac Resynchronization Therapy.

Accessory functions

AV Delay Management

Pacemakers that pace both the atria and the ventricles are programmed to mimic the natural delay in the AV node. This programmed delay (AV delay) can be adjusted and modern pacemakers also allow for rate adjusted AV delay; AV delay is shorter at high heart rates and vice versa. This improves hemodynamics.

Rate responsiveness

Heart rate must increase during exercise in order to increase cardiac output. If the pacemaker is triggered in the ventricle, then the natural increase in atrial rate during exercise will result in a corresponding increase in the ventricular rate. However, this requires that the pacemaker has this pacing mode and that the atrial rhythm is sinus rhythm. Obviously, this is not always the case and therefore some pacemakers are equipped with a sensor that detects physical activity. The sensor may consist of an accelerometer or piezoelectric crystal, both of which detect motions. When the sensor detects physical activity, it increases the ventricular frequency accordingly.

Hysteresis

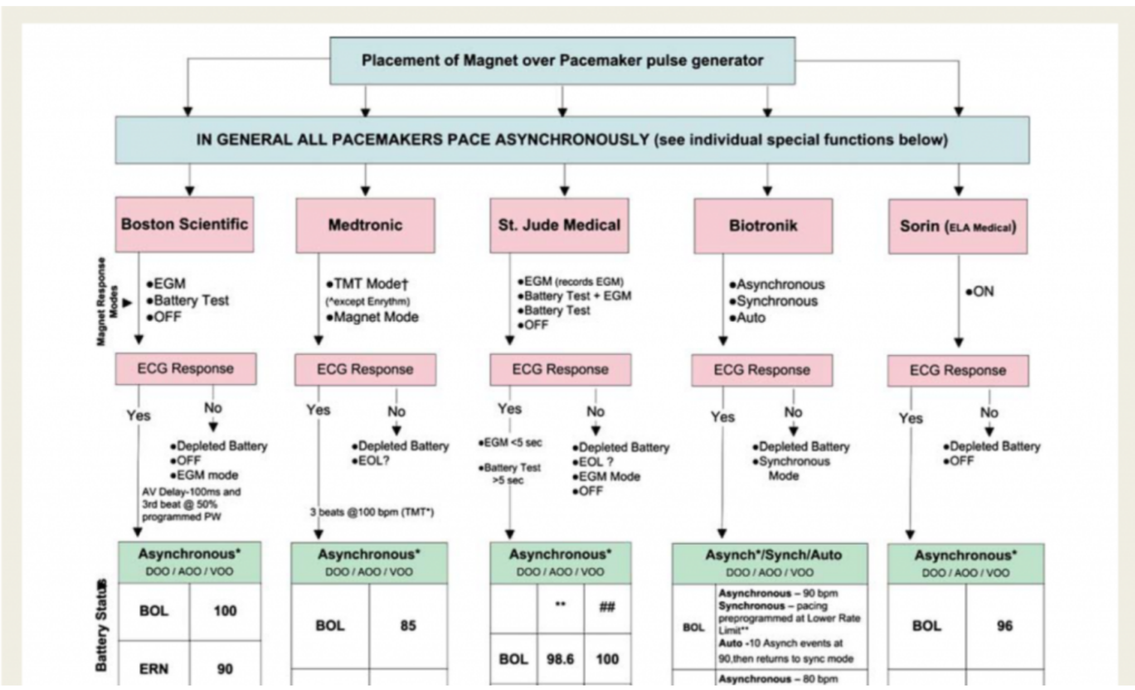
The purpose of hysteresis is to minimize the need for pacing. Hysteresis implies that the pacemaker accepts that the heart rate drops to a certain rate below the base rate, but when that lower rate is reached, then the pacemaker paces at the base rate. This pacing continues for a period of time, whereafter the pacemaker pauses pacing, in order to evaluate whether intrinsic activity (above the hysteresis limit) has recovered.

Mode switch

A pacemaker can, based on pre-programmed algorithms, change its settings. For example, a DDD can switch to DDI if there is atrial fibrillation. The pacemaker makes continuous analyzes of atrial activity to assess whether it needs to change settings.

Magnet effect

Placing a magnet on the pulse generator will affect its functions. The effect varies depending on the type of pacemaker. In general, though, most pacemakers switch to asynchronous pacing (VOO or AOO, or DOO). Figure 3 illustrates the effect of placing a magnet on various pacemakers.



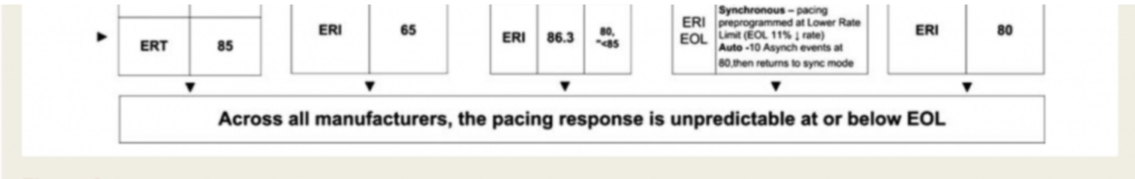


Figure 4. Placement of magnet on a pacemaker.

Biventricular pacing: CRT

A biventricular pacemaker stimulates in both ventricles. This mode of pacing is suitable in situations with pronounced conduction disturbance, which manifests as severe QRS prolongation. Such conduction disturbance results in the desynchronization of ventricular activity, rendering the ventricular contractions less effective, with negative effects on hemodynamics and overall survival in heart failure.

In biventricular pacemakers, the additional lead is placed in the coronary sinus, from where it stimulates the left ventricle (Figure 5). The term **cardiac resynchronization therapy (CRT)** is synonymous with biventricular pacing. CRT reduces heart failure symptoms and prolongs survival.

It is also possible to equip a CRT with a defibrillator (CRT-D), which is appropriate in people at high risk of ventricular arrhythmias.

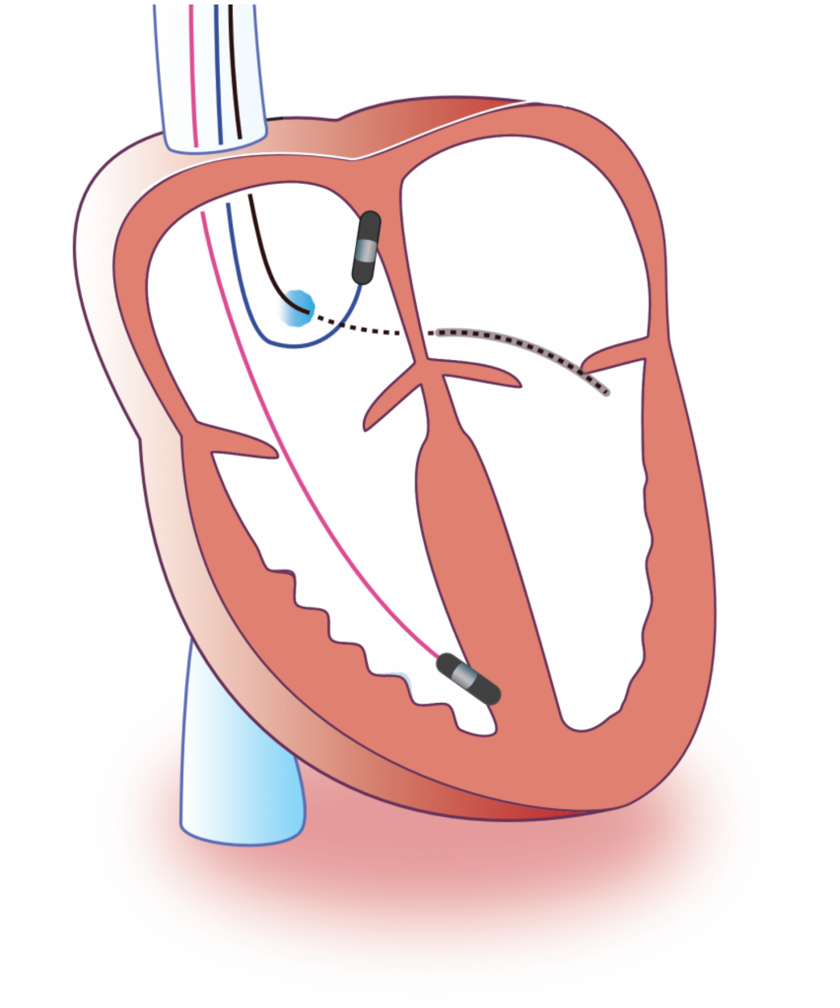


Figure 5. Cardiac resynchronization therapy (CRT)